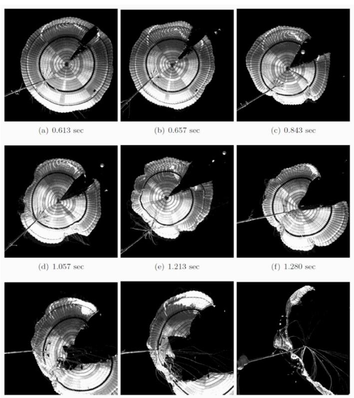
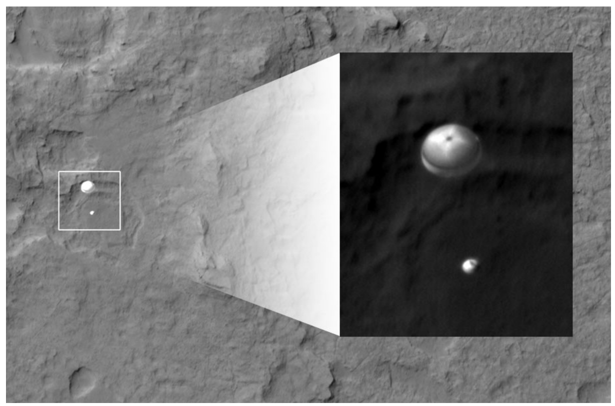
Jet Propulsion Laboratory
California Institute of Technology

Farhat Research Group

Towards a Validated FSI Computational Framework for Supersonic Parachute Deployments





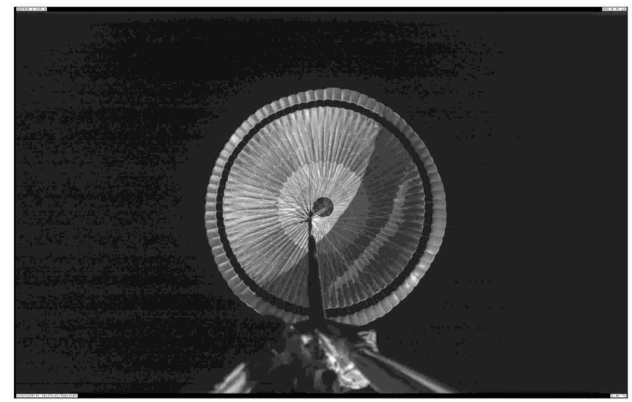


Photo Credit: NASA/JPL, California Institute of Technology

Jason Rabinovitch[1], Daniel Z. Huang[2], Raunak Borker[2], Philip Avery[2], Charbel Farhat[2], Armen Derkevorkian[1], Lee D. Peterson[1]

[1]Jet Propulsion Laboratory, California Institute of Technology
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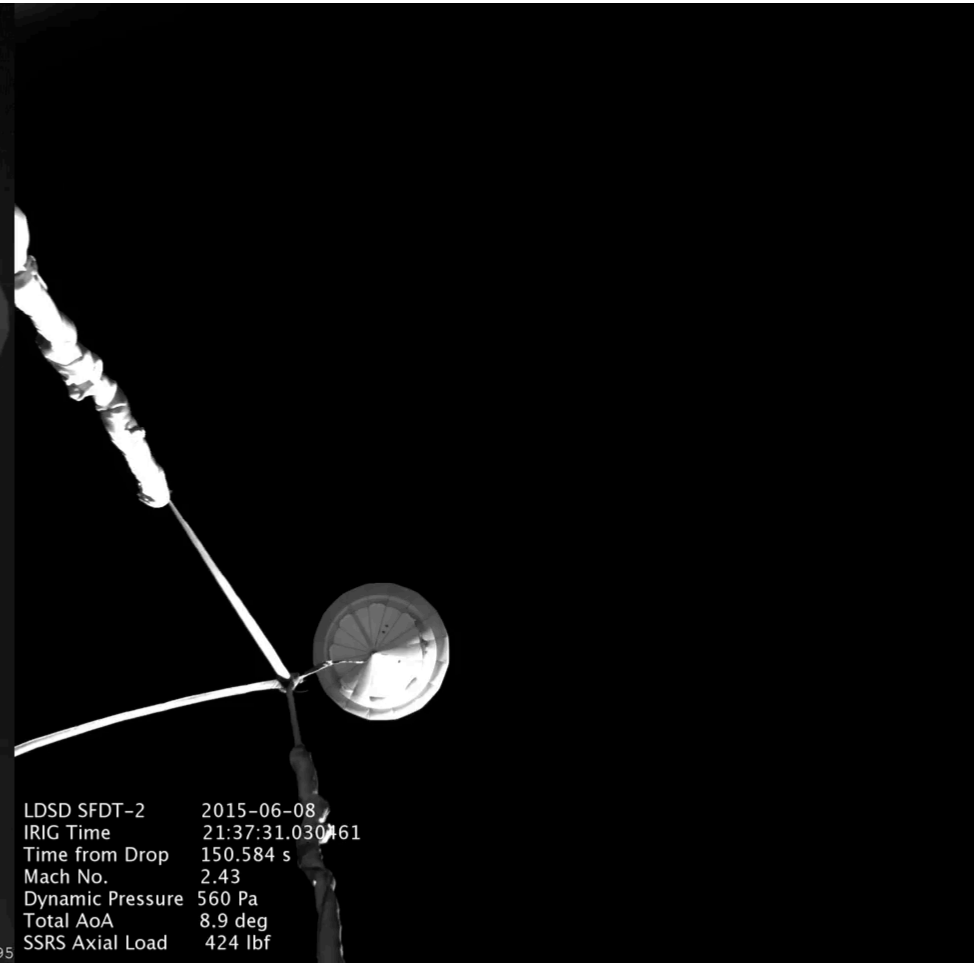
AIAA Aviation 2019

Motivation (LDSD: ~ 30 m diameter parachute)

Disksail Parachute

Ringsail Parachute

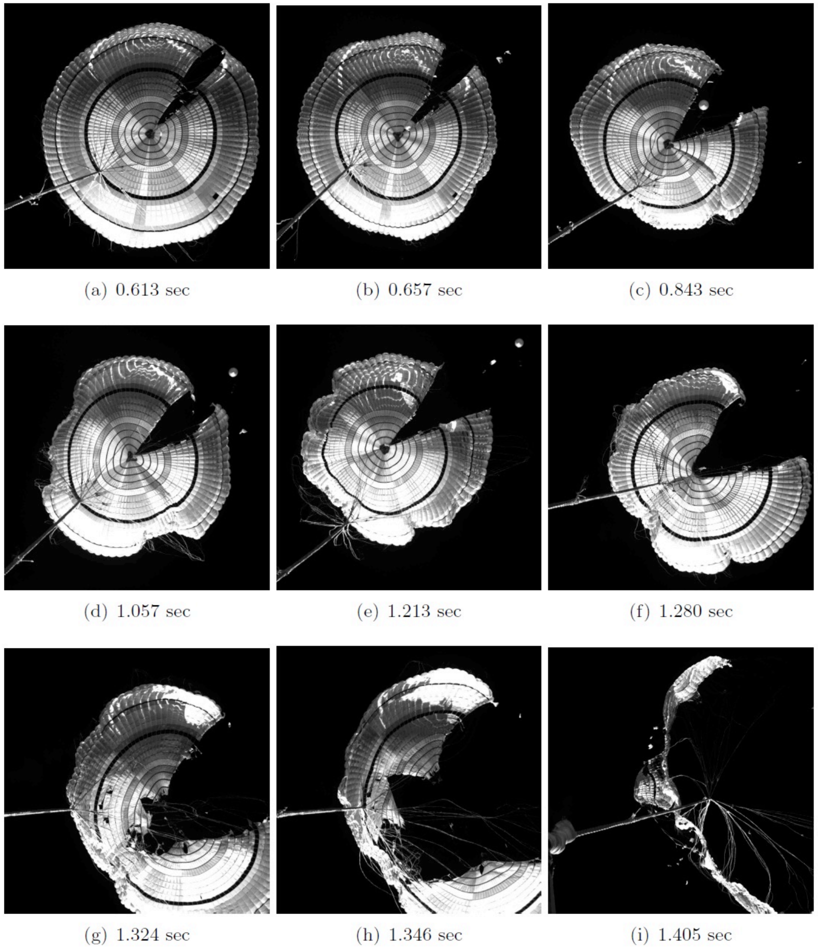


Low Density Supersonic Decelerator (LDSD) project's Supersonic Flight Dynamics Tests (SFDT)
June 28, 2014 (SFDT 1), and June 8, 2015 (SFDT 2)

What went wrong?

- SFDT-1 failed at 9,000 lbf
  - 11% of flight limit load
  - Analytically showed positive margins to a load of 80,000 lbf
- SFDT-2 failed at 79,000 lbf
  - 99% of flight limit load
  - Ringsail analytically showed positive margins to a load of 166,000 lb
- FLL should be the load at which the parachute can safely survive inflation, not its ultimate capability
- Both parachutes were subsonically tested to > 121,000 lbf!

New failure mode observed during supersonic deployment.



Credit: O'Farrell et al., *AIAA-2016-3242*.

Overview

- Objective: Develop a computational framework to accurately model supersonic parachute deployment that could be used as a design tool for future space missions
  - Mars-relevant supersonic tests are time consuming and expensive
  - Currently not feasible to use tests as part of the design process, only for validation
- Highly nonlinear Fluid/Structure Interaction (FSI) problem with large scale deformations
- Rigorous Validation and Verification program is needed before results can be used for design or validation efforts
- Stanford/JPL Collaboration

Embedded Boundary Method

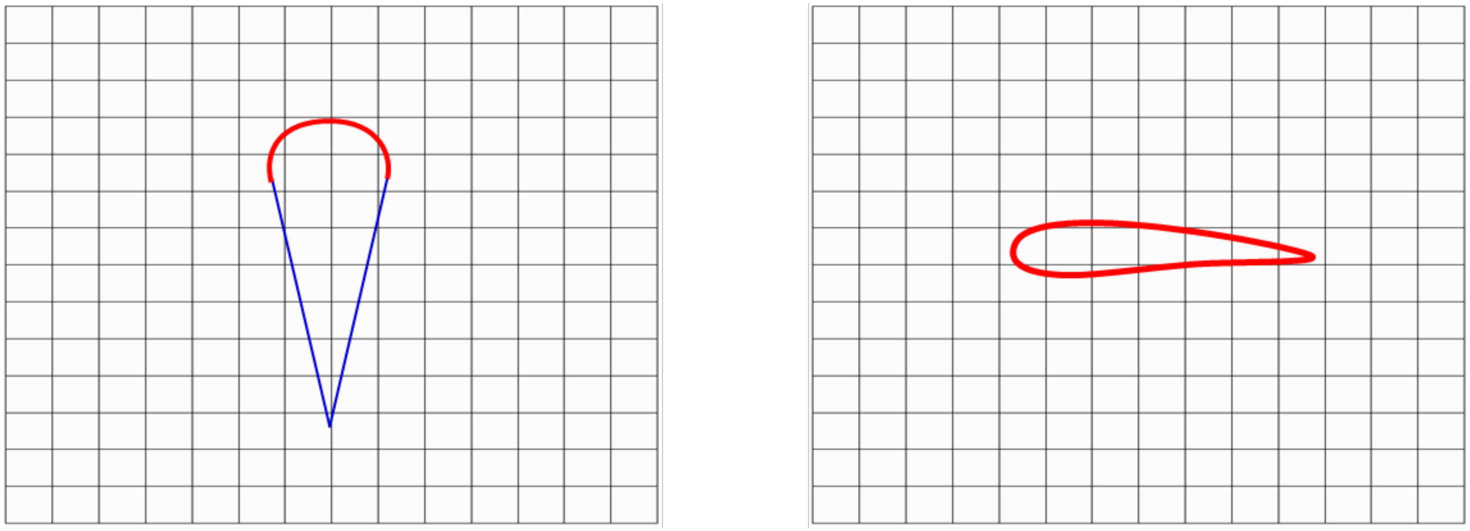
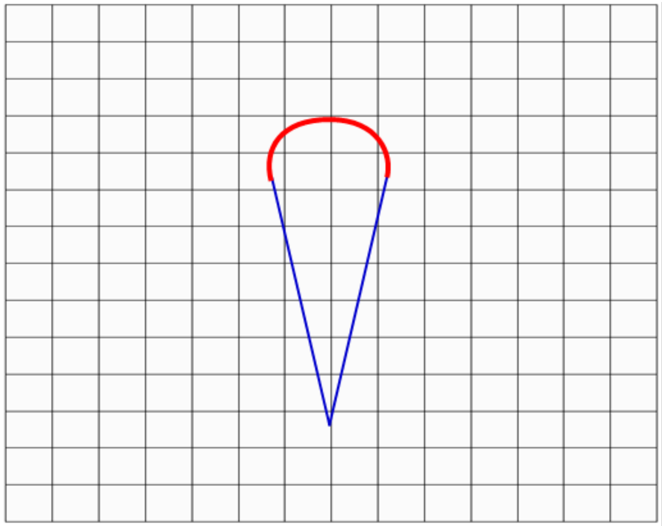


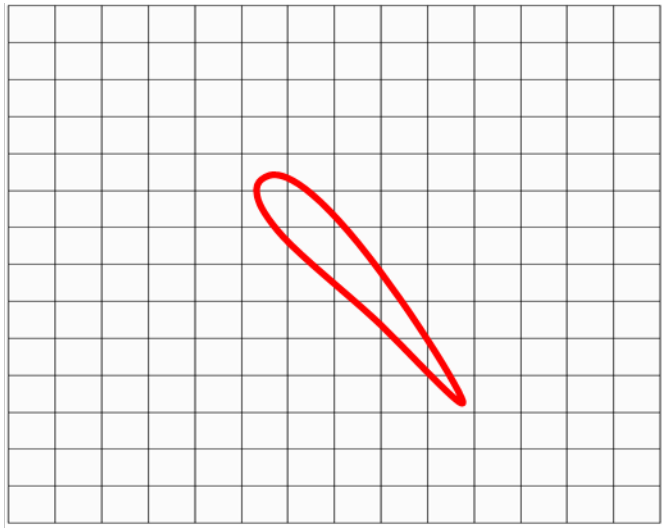
Image Credit: Raunak Borker

- Pros:
  - Allows large structural motion or deformation
  - Simplifies mesh generation procedure
- Cons:
  - Difficult to create a mesh that will track a boundary layer without Adaptive Mesh Refinement (AMR)
  - Complicated numerical treatment required for the fluid/structure interface

Huang et al., *JCP*, 2018

Embedded Boundary Method





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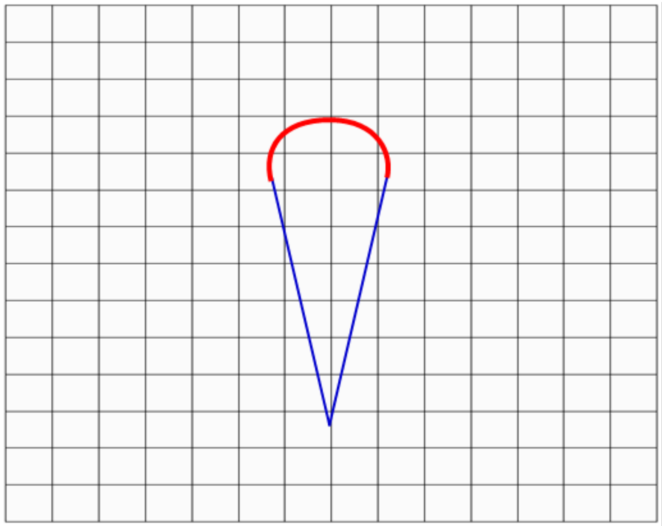


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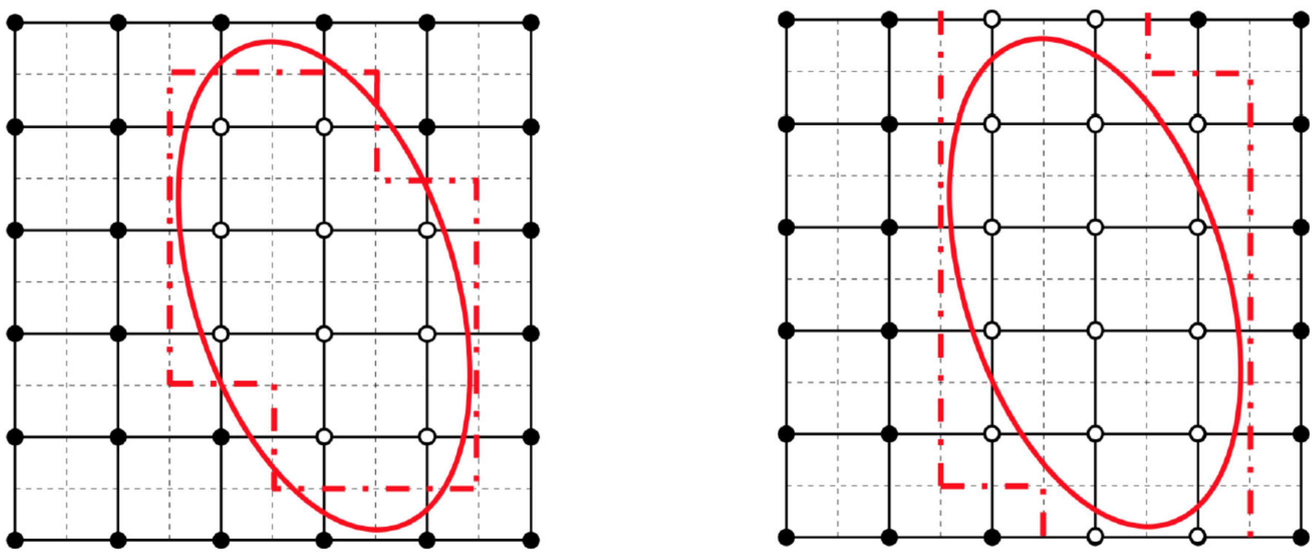
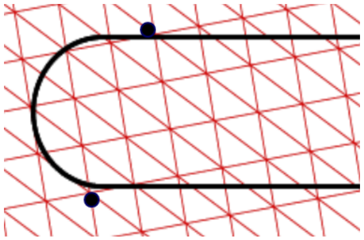
Huang et al., *JCP*, 2018

Embedded Surface Numerical Framework

- Finite Volume method with Exact two-material Riemann Problems (FIVER)
  - Huang et al., *JCP*, 2018, Main et al., *JCP*, 2017, etc.
- Analytical Riemann problem at fluid/structure interface



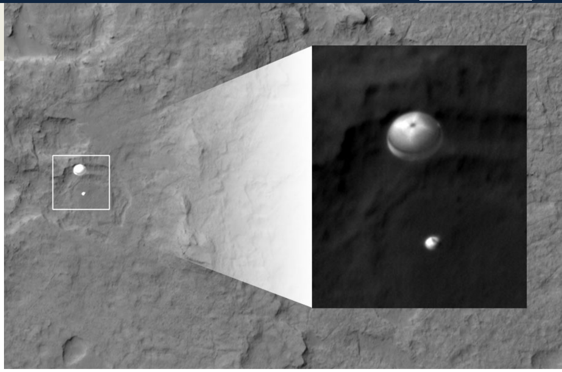


ill-conditioning

Fig. 4.2. Surrogate material interfaces (two-dimensional illustration where a circle filled with a black/white color designates an active/inactive node, and the continuous and dashed lines in red color represent the true and surrogate material interfaces, respectively): case of the node-based definition of the status of a node (left); and case of the control-volume-based definition of the status of a node (right).

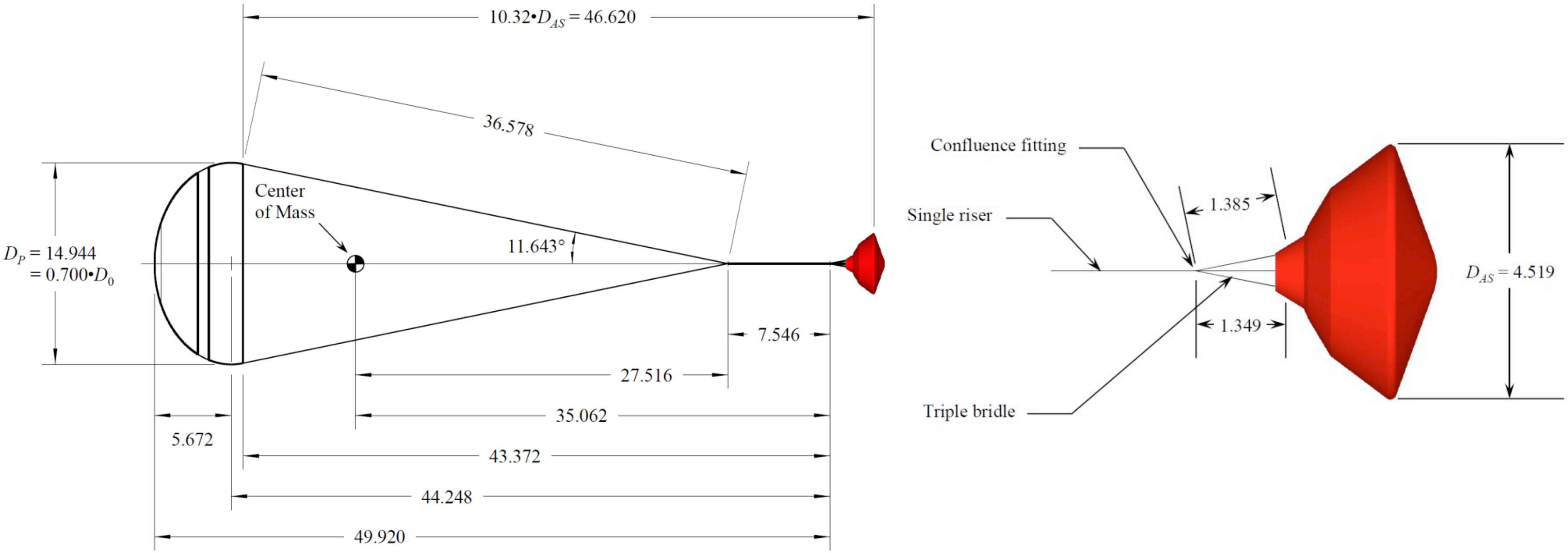
Recent Code Additions and Focus

- Supersonic parachute deployment specific updates
  - AMR (cite AMR paper)
    - Distance to surface
    - Hessian criteria
    - Intersecting edges
  - Porous surface modeling
    - Compared to DNS and experimental data
  - Smooth forces with embedded framework
  - Self-contact
  - Minor fixes to run on 1000+ cores
- Simulation Focus
  - Preliminary investigation of drag force sensitivity to LES/RANS modeling
  - Effect of suspension lines



System Level Simulation Plan

- AERO Suite
  - Entry vehicle – embedded surface
  - Triple bridle, riser, suspension lines, canopy – embedded surface



MSL Parachute Schematic (Cruz et al., AIAA 2013-1250)

Free Stream Conditions

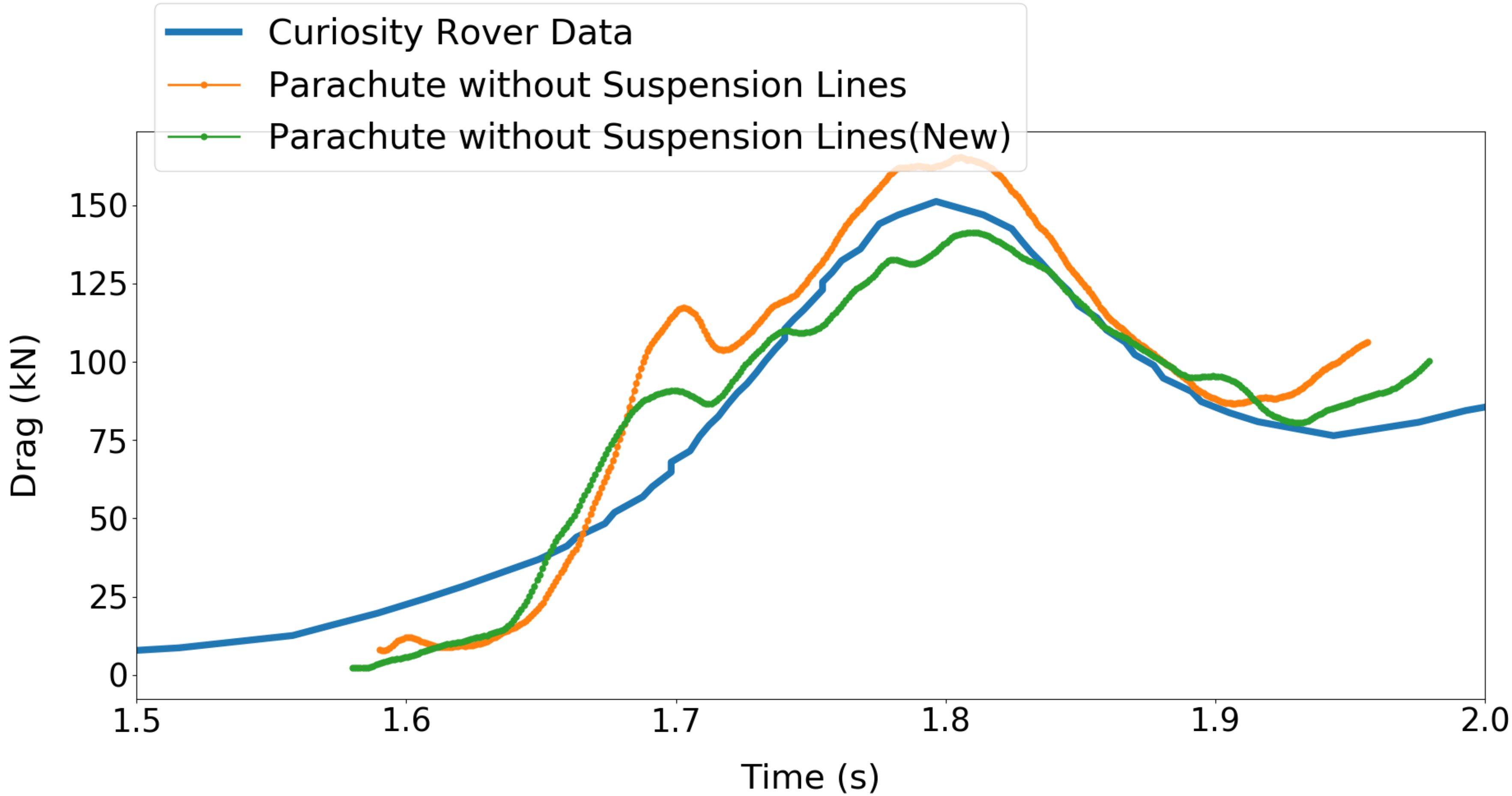
Original Freestream

- Gas: CO2
- Density =
- Mach Number =
- Pressure =
- Temperature =
- Capsule Re ~=
- Viscosity – Sutherland's law
- LES -

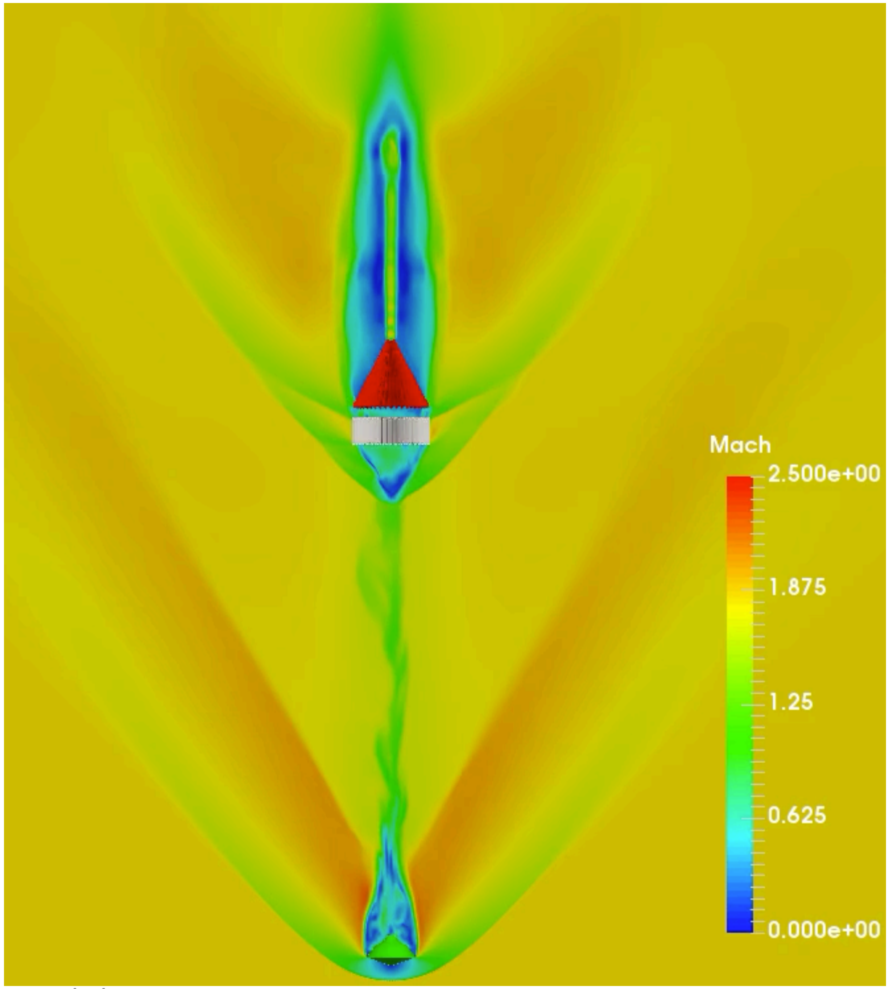
Updated Freestream

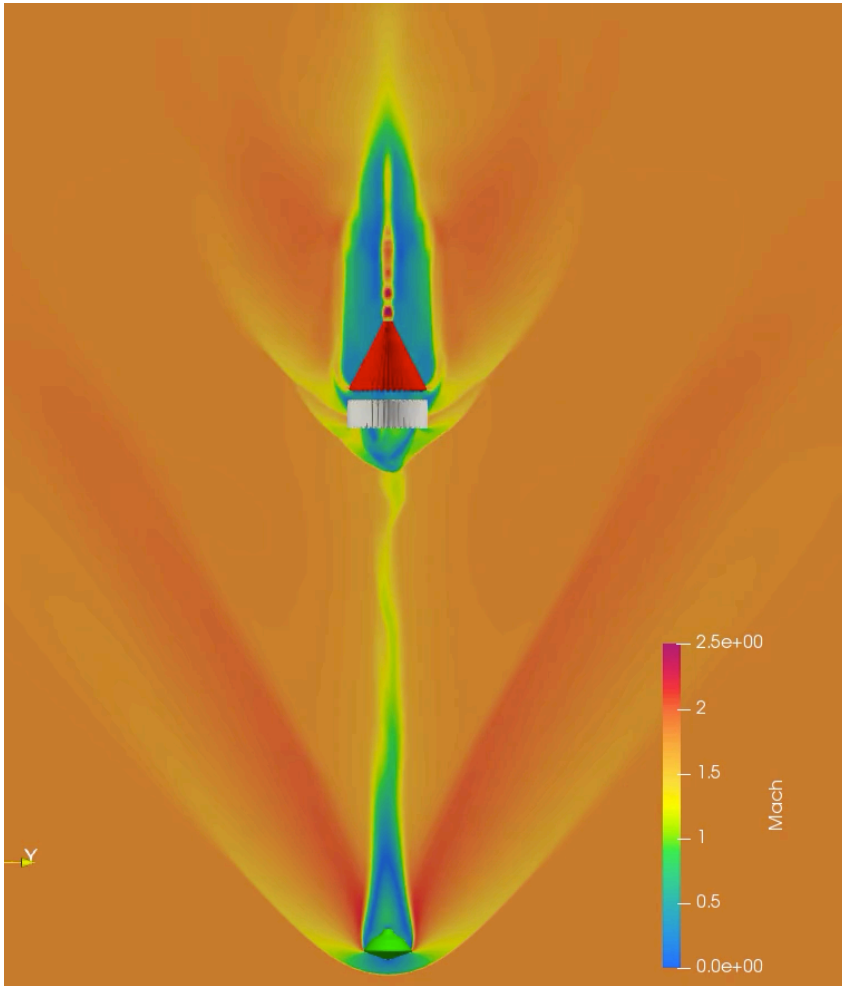
- Gas: CO2
- Density =
- Mach Number =
- Pressure =
- Temperature =
- Capsule Re ~=
- Viscosity – Sutherland's law and bulk viscosity
- LES -

Preliminary Results: Updated Initial Conditions



Preliminary Results: RANS vs LES





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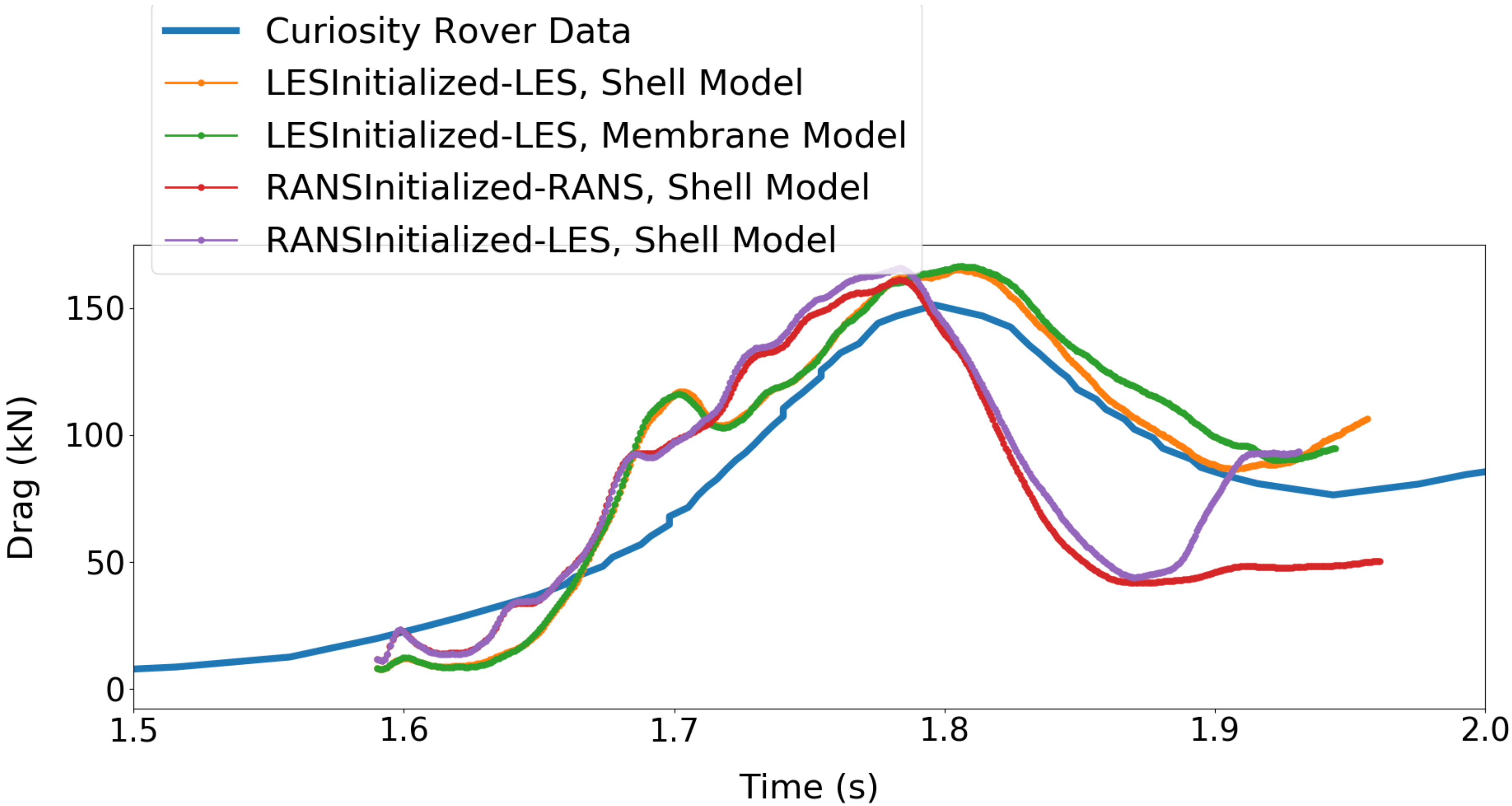
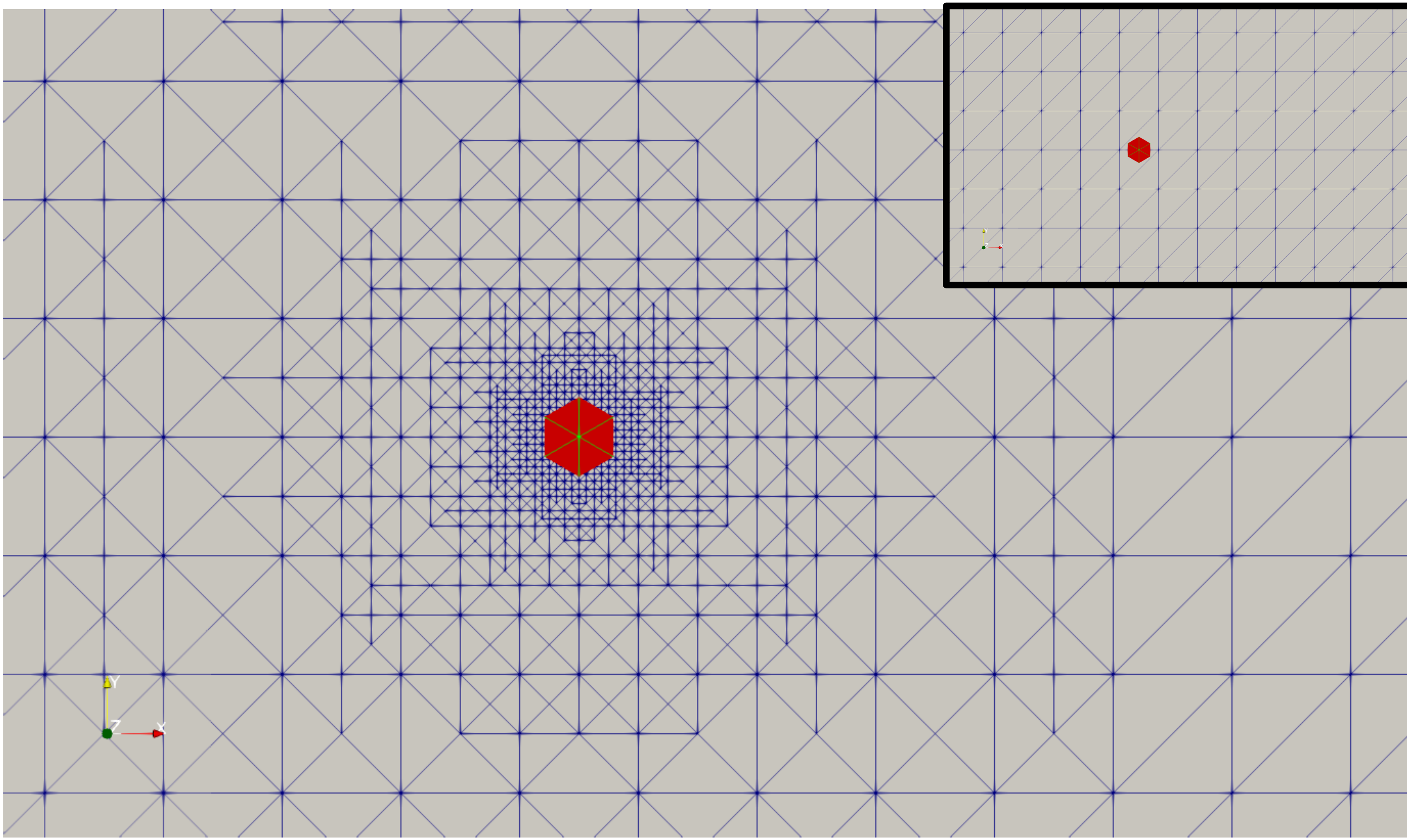
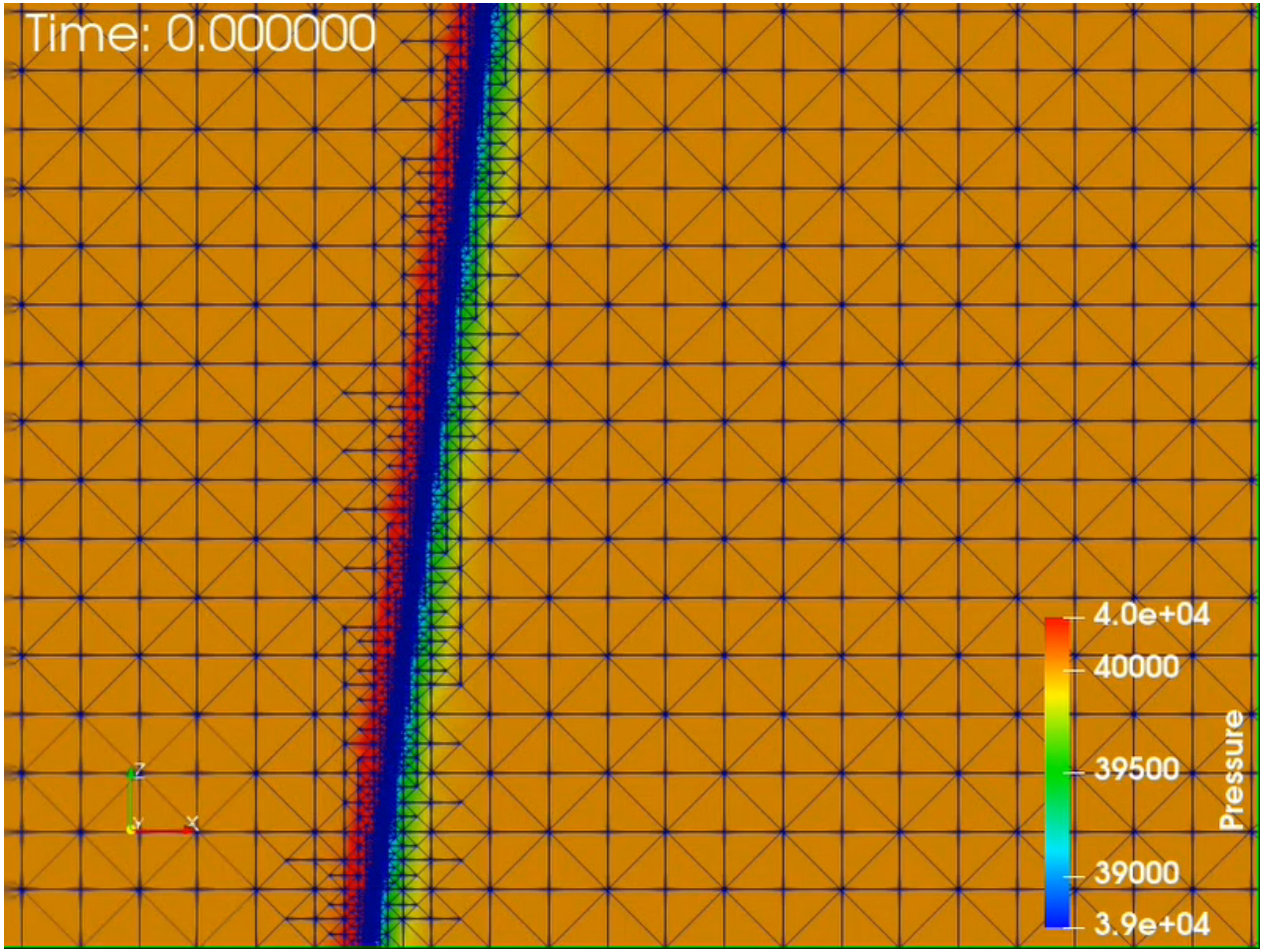


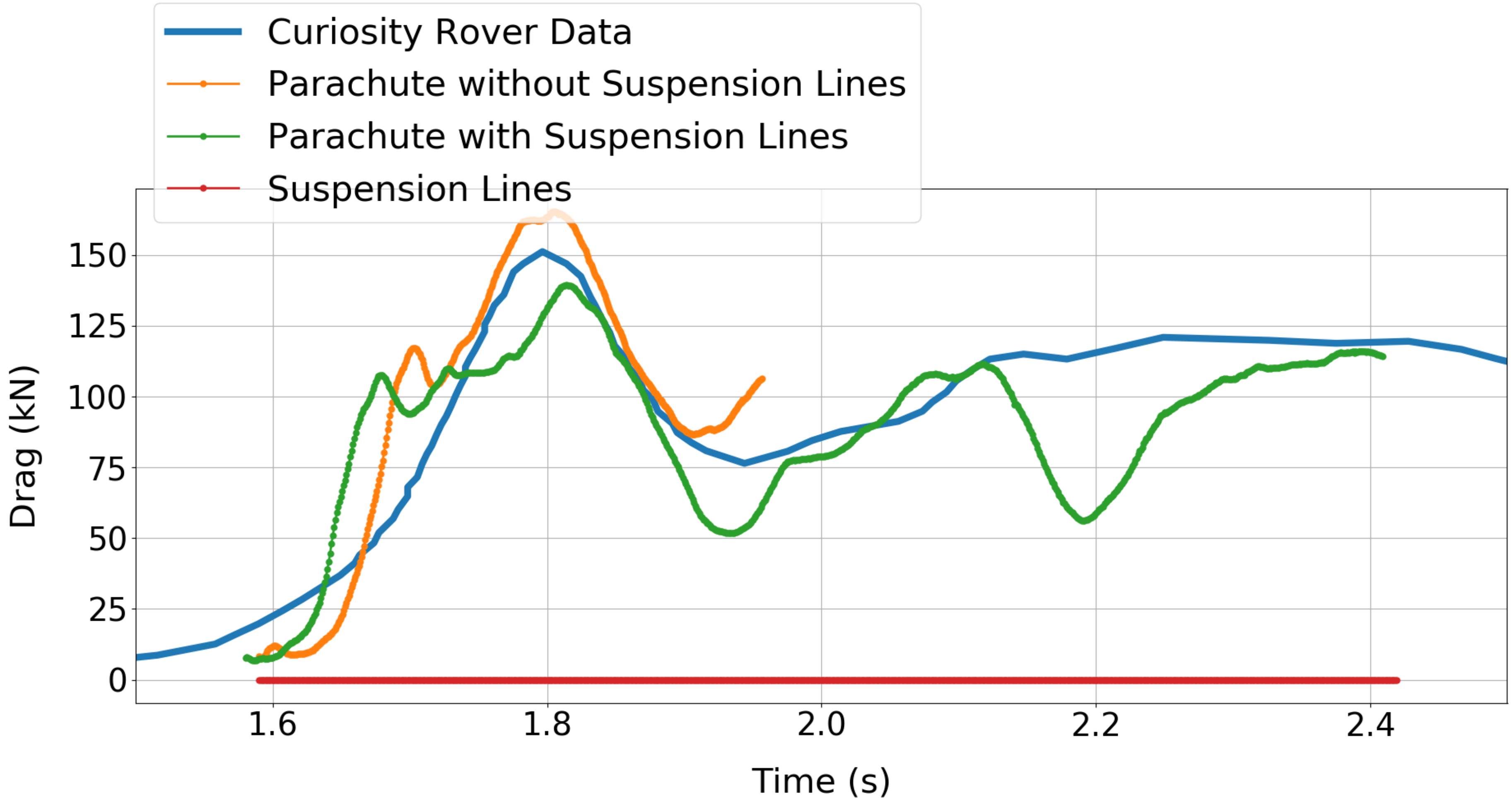
AMR for Suspension Lines



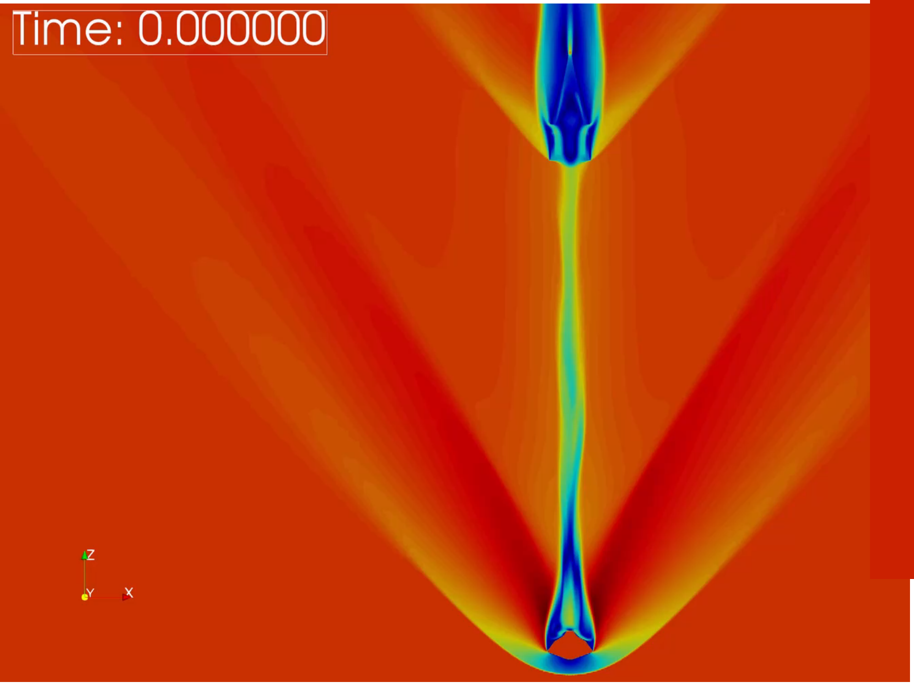
AMR for Suspension Lines

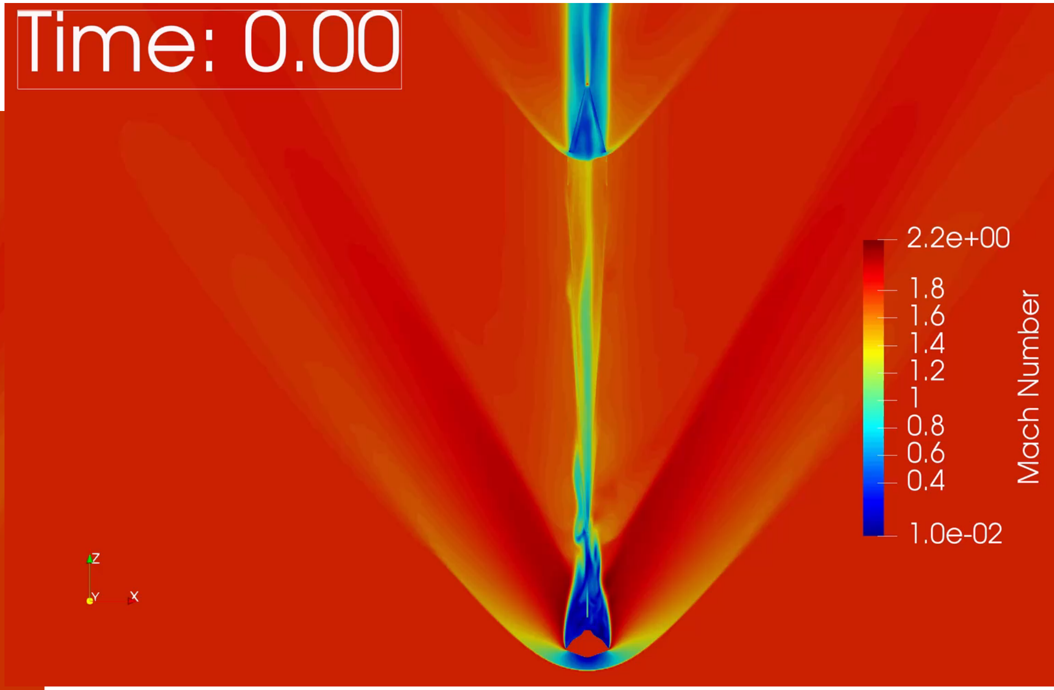


Preliminary Results: Effect of Suspension Lines



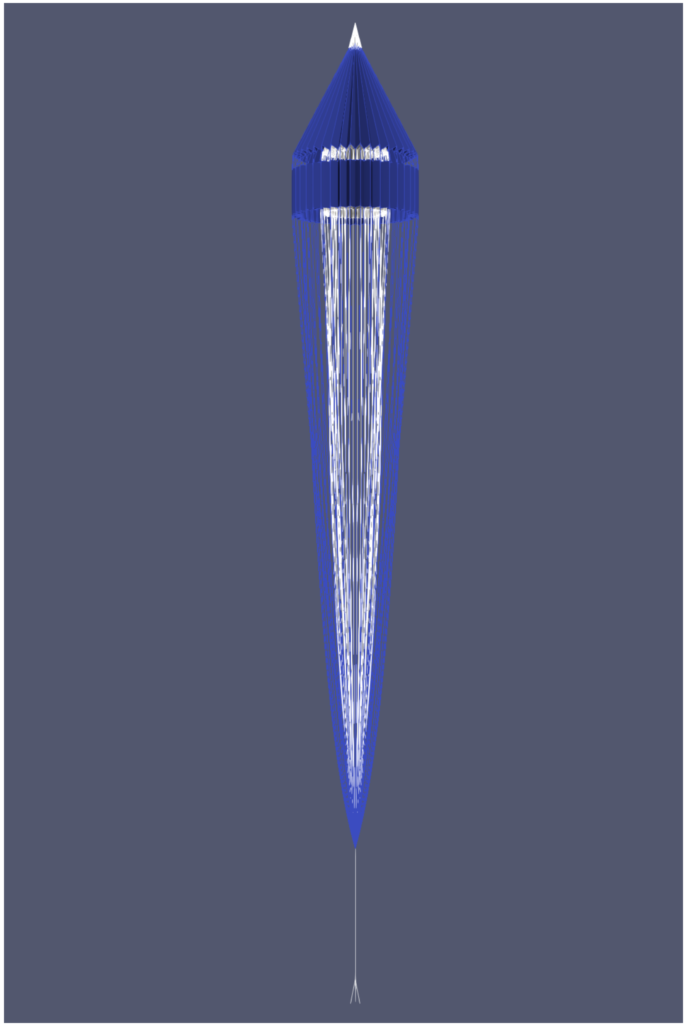
Static Structure LES Simulations



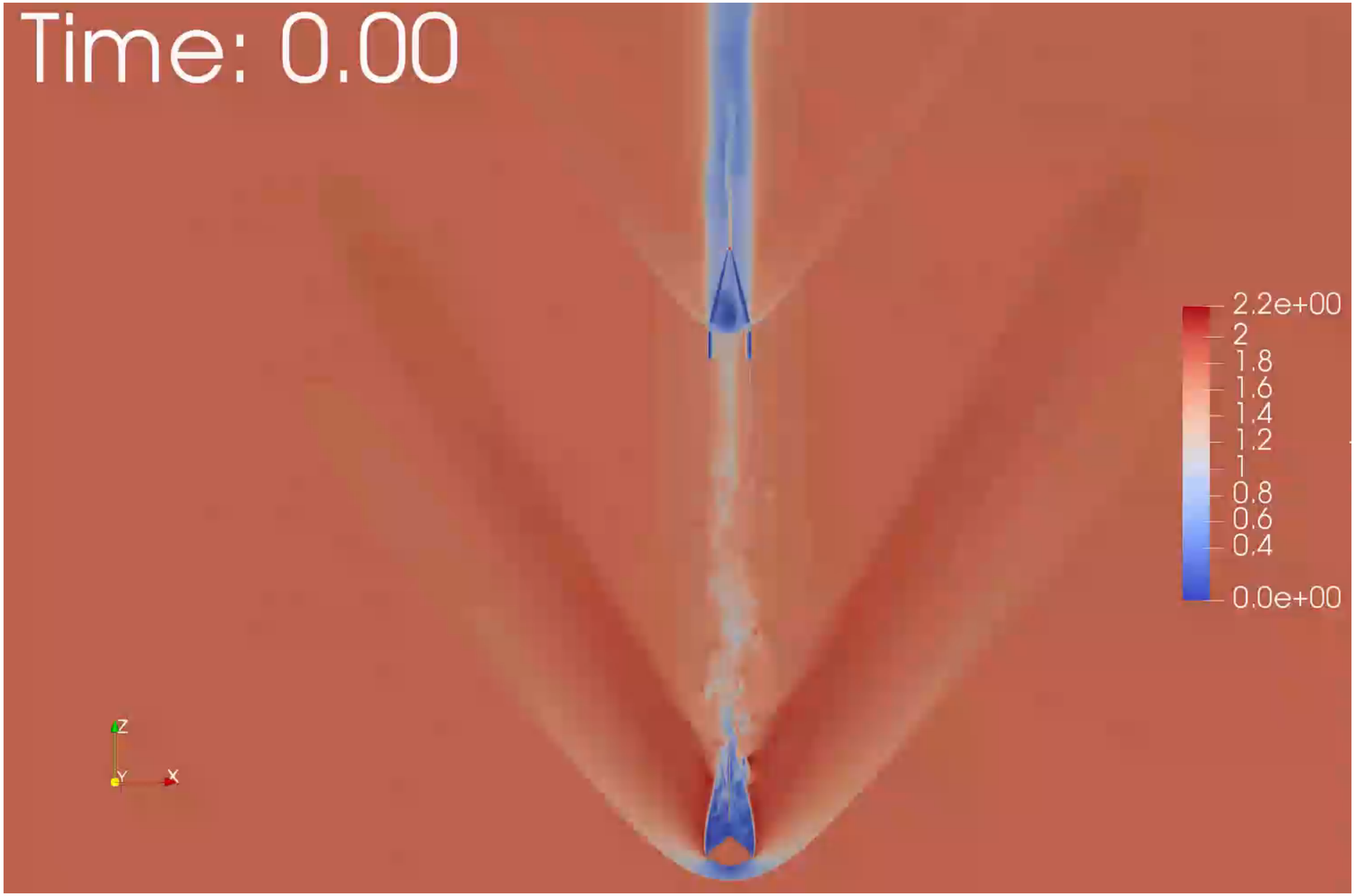


Ongoing Work

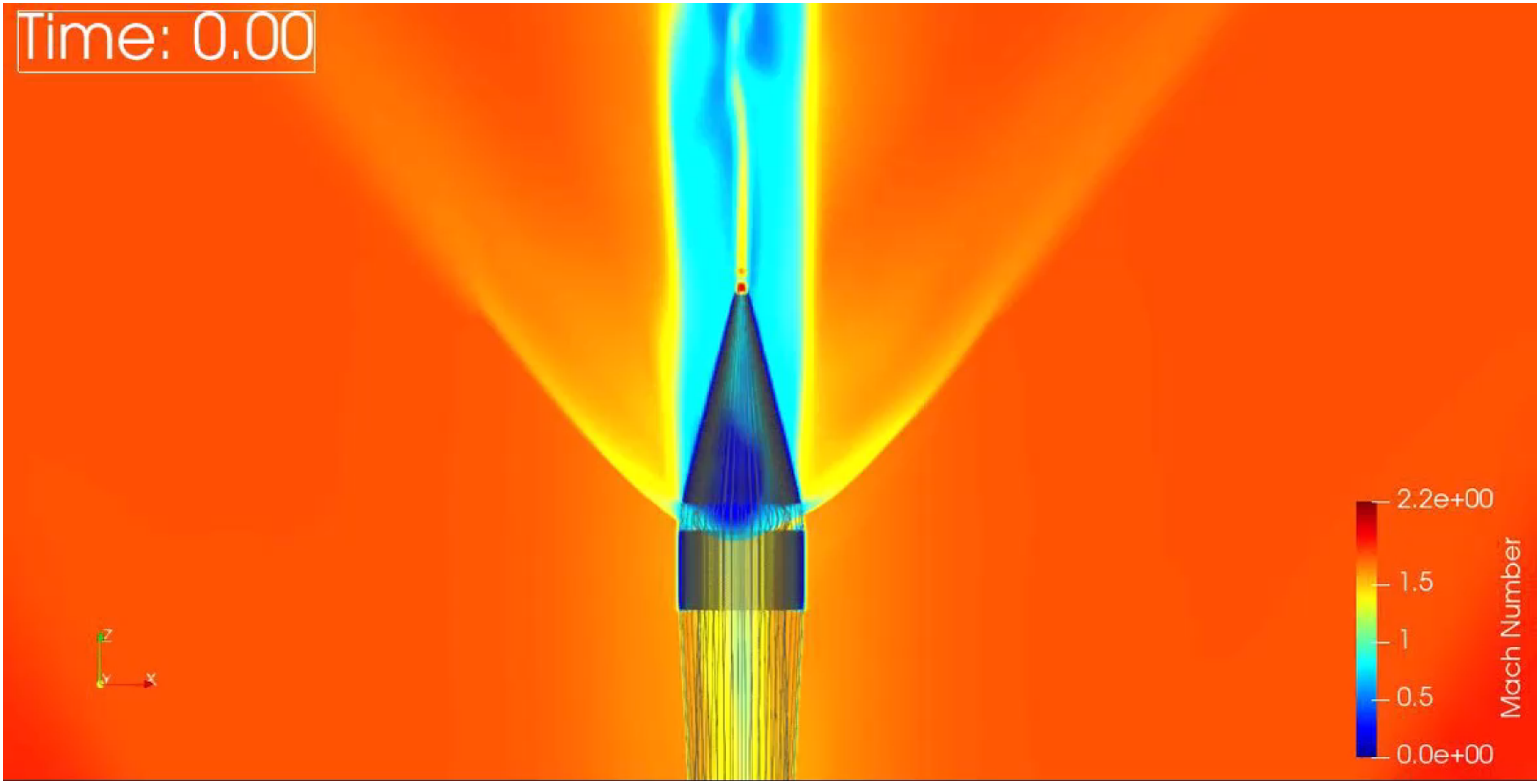
- Sensitivity of results to initial parachute model
  - Geometry
  - Pre-stressed or zero stress-state
- Time required for LES simulation
- Resolution requirements (fluid and structure)

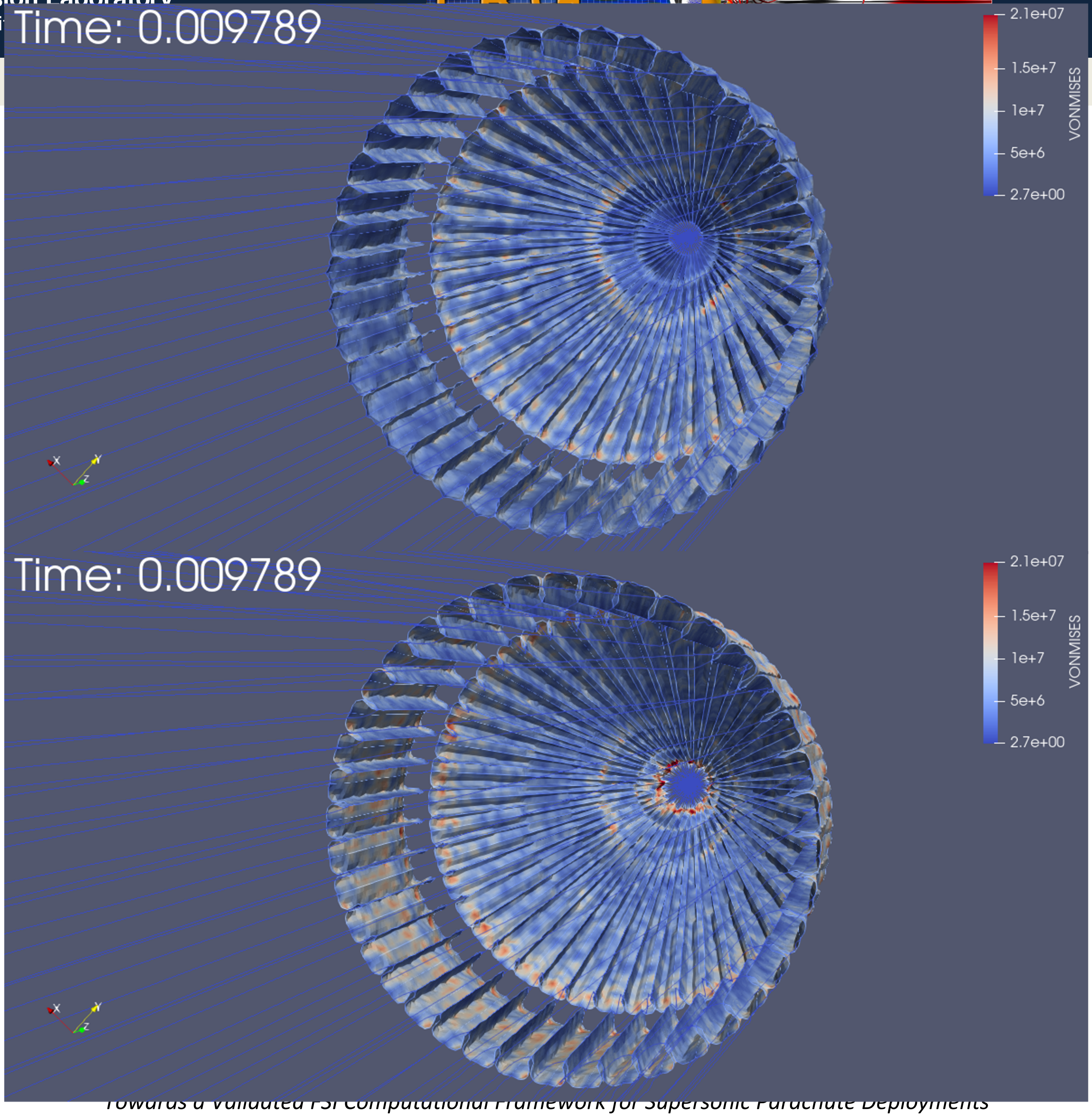


Preliminary FSI Simulations



Preliminary FSI Simulations

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Time: 0.009789
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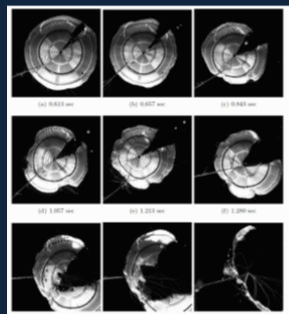

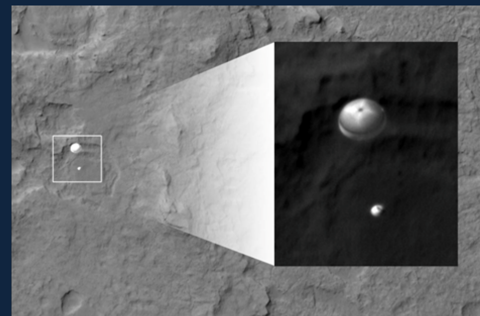

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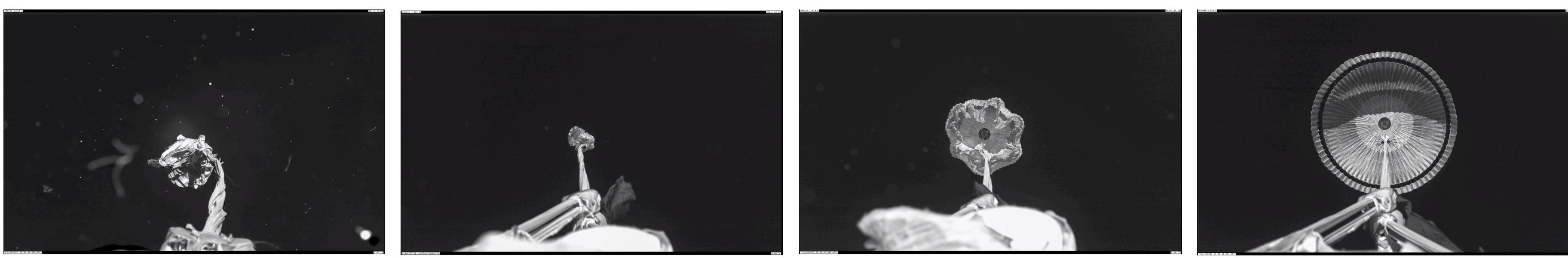
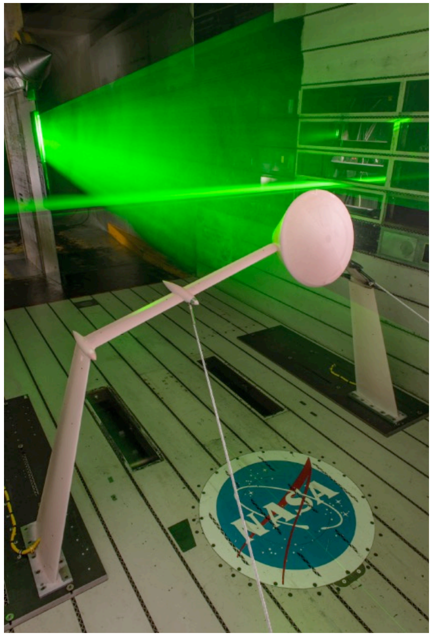
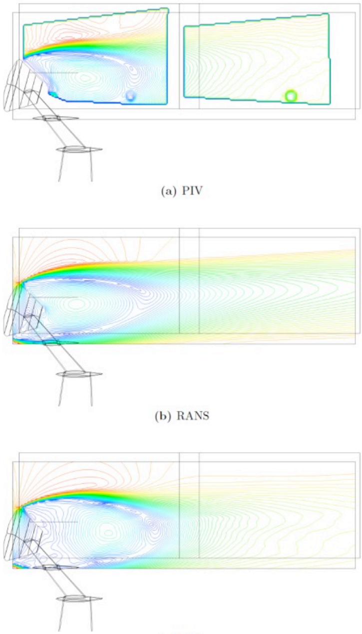


ASPIRE Supersonic Parachute Flight Test, Oct. 4, 2017
https://www.jpl.nasa.gov/video/details.php?id=1507

Capsule Simulation

- Recent works have highlighted discrepencies between numerical simulations and experimental data for compressible capsule flow (Murman et al., AIAA-2015-1930)
  - Influence of turbulence models, surface roughness, mesh refinement, Riemann solver, etc.

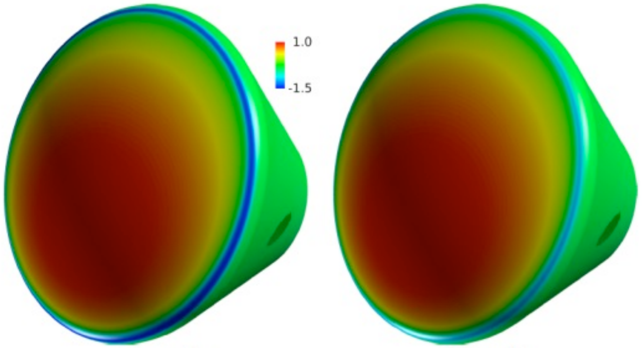




(a) PIV

(b) RANS

(c) DES

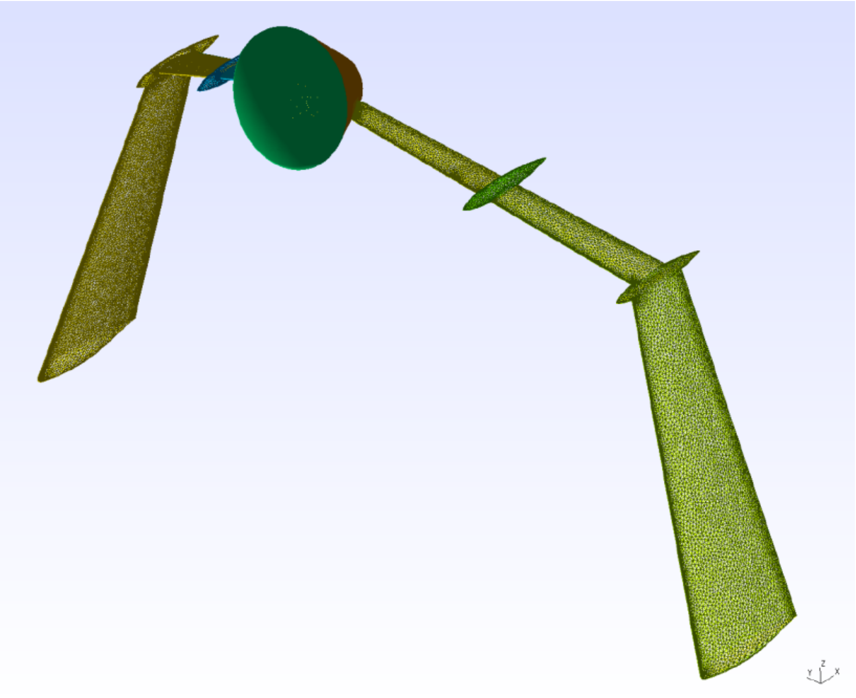


(a) smooth (b) rough

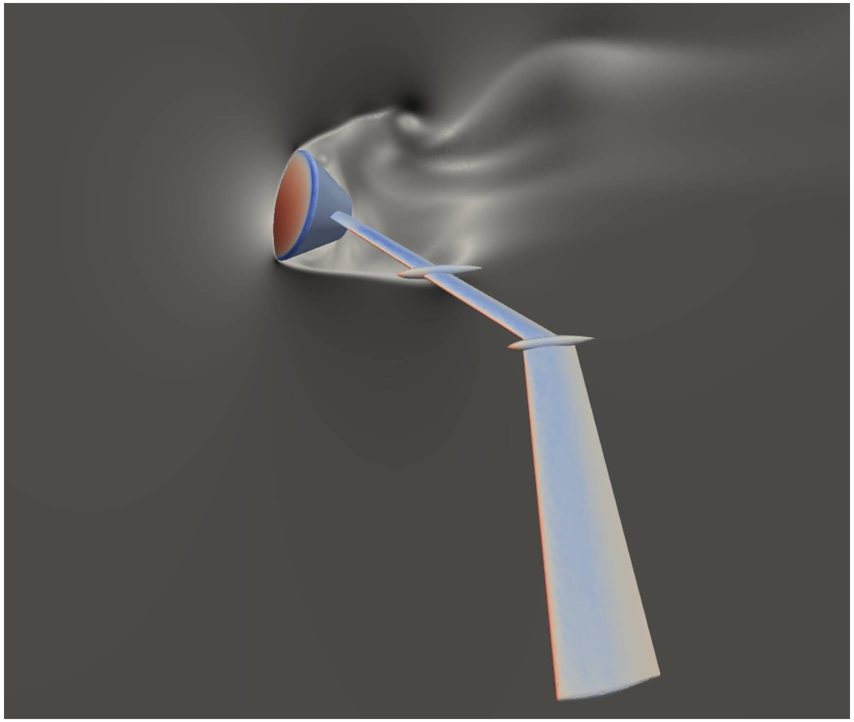
Images taken from Murman et al., AIAA 2015-1930. From left to right: experimental set-up in NASA Ames 11ft transonic tunnel, comparison between numerical and experimental results, and CFD surface pressure results.

Capsule Preliminary Results

- Work in progress
- Good candidate for new AERO-F AMR capabilities (Borker et al., AIAA-2018-1072)
- Parachute deployment sensitivities to wake properties is a large unknown



Surface geometry used in AIAA-2015-1930 generously provided by Scott Murman



Preliminary Simulation